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Enabling Interoperable Distributed Ledger Technology with Legacy Platforms for Enterprise Digitalization

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Abstract

Digitalization is important to realize enterprise sustainability, where processes, data, systems, and stakeholders are in a seamless connected environment. Presently, to achieve enterprise digitalization technologies such as Distributed Ledger Technologies (DLT) has now been deployed to support digital services provided by enterprises. Hence, there is significant interest in the adoption of DLT to offer better visibility of data among several stakeholders and systems in a decentralized peer-to-peer topology. But several challenges in DLTs remain to be addressed, including the interoperability, standardization, and integration of DLTs. Similarly, research on DLT interoperability is scarce and this has hindered the wide-spread adoption of DLTs, and interoperability is a critical requirement for the resilience and scalability of DLTs. However, almost all DLTs are siloed apart from a few DLTs such as Hyperledger Fabric or Ethereum, most DLTs are deployed for specific applications and typically do not communicate and interact with each other. Hence there is need to explore how interoperability of DLTs such as IOTA Tangle can be achieved with legacy systems. Therefore, this study provides theoretical and practical understanding of DLT interoperability and identified the factors that influence the interoperability of DLTs. Also, an architecture that shows how interoperability can be achieved in DLTs and legacy systems grounded by Application Programming Interface (API) standardization is presented. A case study is presented based on the applications of IOTA Tangle in the architecture for buying and selling of energy showing the potential of DLT for enterprise digitalization. The findings from the case study are modelled in ArchiMate to illustrate the applicability of the architecture for a realistic use case that depicts how IOTA Tangle and API are implemented to support a digital energy marketplace.

Keywords: Enterprise digitalization; Distributed ledger technologies; Interoperability; Architecture modelling; IOTA tangle; Case scenario.

1. Introduction

Distributed Ledger Technology (DLT) is believed as an enabling infrastructure for enterprise processes and systems (Chen et al., 2020; Belchior et al., 2021). It allows enterprises to achieve digital transformation of their current business models by eliminating intermediaries, decreasing costs, and enhancing trustworthiness among partners, thus enabling a new trend of decentralized platform-based services (Lima, 2018; Lohachab et al., 2021; Asante et al., 2021). Findings from the literature suggest that DLTs such as Ethereum, Corda, Ripple, Hyperledger Fabric, blockchain, IOTA Tangle, etc. proposes great potential to support the exchange of immutable and secure data across different stakeholders (Hardjono et al., 2019; Hawig et al., 2019; Anthony Jnr, 2023a). DLT offers the next-generation decentralized internet of value, where assets and digital transactions are authenticated, and maintained in a distributed ledger creating a new model for enterprise digitalization (Lima, 2018; Madine et al., 2021). DLTs are now becoming the underlying infrastructure for digital transformation creating a new trend of decentralized platforms and applications, referred to as dApps (Lima, 2018; Carter et al., 2019), that will be deployed to replace most of the centralized cloud-based systems used in enterprises today.

Currently, the DLT landscape is mostly fragmented as there are no consistent standardization among different platforms and technologies. It is not likely that there will be one ledger to rule them all (Koens and Poll, 2019). Thus, existing DLTs platforms operate in silos as standalone and isolated without communicating with other DLTs and legacy systems. Therefore, interoperability has become an important issue to support broad DLT adoption towards sustainable enterprise digitalization (Hewett et al., 2020; Hardjon et al., 2020). Subsequently, DLT interoperability which comprises of an internet of DLTs, inter-DLT communication and DLT platformization have become trending issues. Besides, interoperability of DLTs aims to achieve trust among partners ensuring that all business stakeholders can communicate across a single platform as well as across different platforms (Hewett et al., 2020).

Interoperability is considered as a top issue for businesses interested in implementing DLT based solutions (Hewett et al., 2020), so as not to limit their collaborative capabilities with partners which implement other vendor locked platforms. Enterprises are interested in adopting scalable digital solutions that can develop within the enterprise and across the extended ecosystem if required (Reegu et al., 2021). Likewise, most enterprises intend to remain flexible in connecting or changing to different digital solutions. Concurrently, other enterprises are interested with how to make their existing infrastructures interoperable with DLT platforms, usually to send and receive data from a deployed DLT solution (Hewett et al., 2020). Evidently interoperability is one of enterprise requirements needed for the survival and mass adoption of DLTs in improving enterprise digitalization (Lima, 2018; Anthony Jnr and Abbas Petersen, 2021). The lack of interoperability amongst platforms deployed in enterprise process may result in a decreased level in terms of quality of service and loss of financial resources (Reegu et al., 2021). Interoperability in enterprise today reflects the secure and seamless exchange of data digitally between authorized partners (Reegu et al., 2021). Although, findings from the literature (Koens and Poll, 2019), stated that the interoperability of DLTs platforms may have an impact on the integrity of the distributed ledgers or even make digital transaction to becomes economically not viable.

Therefore, this study adds to the body of knowledge by examining the following research questions.

- How to achieve interoperability of DLTs with existing legacy platforms deployed for enterprise digitalization?
- What are the factors that influence the interoperability of DLTs for enterprise digitalization?
- What are the open challenges and possible recommendations for DLT interoperability for enterprise digitalization?

Therefore, several enterprises are currently working to develop a mutual set of standards focused on improving data availability and interoperability which are crucial for the survival and mass deployment of DLT as an enabler of digitalization of enterprises (Lima, 2018). To this end, over the past decade enterprises are adopting a variety of digital solutions and tools such as enabling Application Programming Interfaces (APIs) that aim to improve the interoperable exchange of data (Hawig et al., 2019; Masuch et al., 2020; Anthony Jnr, 2021). Therefore, this study aims to provide an ideal design for a DLT-based solution for data exchange with legacy platforms. Grounded on a developed enterprise architecture framework this study depicts how IOTA Tangle (a directed acyclic graph based DLT) and APIs are employed to achieve an interoperable data sharing to aid digitalization of enterprise process within the +CityxChange project (https://cityxchange.eu/). IOTA Tangle was selected as a supporting DLT due to its data traceability, immutability, and tamper-proof attributes. IOTA Tangle provides flexibility and performance to enable a reliable environment for interoperability within enterprise process. The remainder of this article is arranged as follows: Section 2 is assigned for literature review and theoretical overview related to factors that influence the interoperability of DLTs. The method employed through an architecture which integrates different technologies, is presented in section 3. Section 4 outlines result of a case study based on the applications of IOTA Tangle and API in the architecture for validating the potential of our approach through a digital energy marketplace scenario. Then section 5 is the open challenges and recommendations for DLT interoperability. Next, section 6 is the discussion and implication of the study. Finally, section 7 outlines the conclusion, limitations, and future research directions.

2. Literature Review

2.1. Interoperability for Enterprise Digitalization

Karoudis and Magoulas (2018) cited Wegner (1996) and stated that interoperability is defined as the capability of two or more software components or systems to connect and exchange data thereby overcoming differences in execution platform, interface, and language. The fundamental types of interoperability to be achieved for enterprise digitalization comprises of syntactic interoperability, semantic interoperability, and structural interoperability as seen in Figure 1.

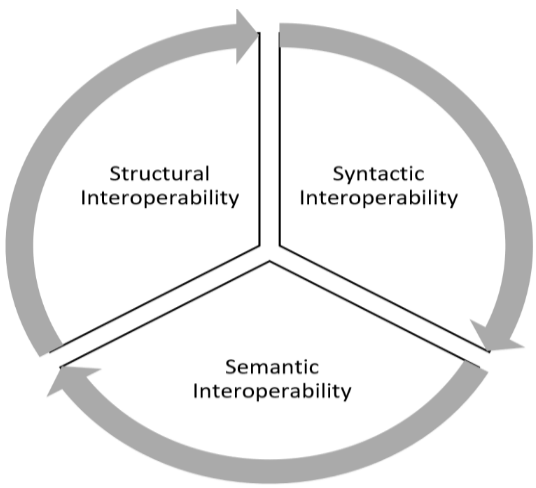

Figure 1. Fundamental types of interoperability in enterprise

Syntactic interoperability describes the packaging and transmission structures for data communication and exchange among two or more systems irrespective of the systems having different interface and programming languages (Firdaus and Rhee, 2020). In DLTs syntactic interoperability involves the ability of distributed ledgers to speak with each other based on specified communication protocols and data formats. Syntactic interoperability is also described as language interoperability as it concerns the communication and exchange of data between digital platforms at the application level (Bokolo, 2022). It ensures the capability of different digital systems and applications to interpret and understand the syntax of the data in the same way (Karoudis and Magoulas, 2018). Syntactic interoperability helps to resolve the lack of common data standards (i.e., conventions, dictionaries, and models) which facilitate the interpretation of data across platforms deployed in an enterprise. It facilitates efficient data re-usability based on a standard format different from the specified data environment (Sun et al., 2020).

On the other hand, semantic interoperability is the ability of software systems to exchange data with definite shared meaning. Semantic interoperability refers to logical interoperability as it aims to overcome the differences between digital platforms at the knowledge/meaning level. Semantic interoperability enables data to be exchanged and understood between two or more digital platforms (Hardjono et al., 2019). Digital platforms exchange data based on pre-established, negotiated, and shared meanings of information terms and expressions (Karoudis and Magoulas, 2018). This is achieved by adding information (metadata) about the data (Anthony et al., 2019), connecting each data component to a managed, shared vocabulary. In DLTs semantic interoperability is also referred to as semantic homogeneity as it aims to achieve agreements regarding the interpretation, meaning, or intended use of the same data. Lastly, structural interoperability involves the possibility of addressing the differences of digital platforms mainly at the access level by considering the application programming interfaces, deployed communication protocols, etc.

Respectively, enterprise information systems utilize different digital platforms that uses different representations for similar data, for example conceptual structures and distinct syntactic, interpretations or terminologies of similar terminology. But, achieving semantic and syntactic interoperability is challenging since it requires alignment among different applications, especially in a dynamic open eco-system environment. Presently to achieve a enterprise digitalization structural interoperability can be achieved by employing API as RESTful web services (Karoudis and Magoulas, 2018; Jnr et al., 2020). Also, JavaScript Object Notation (JSON) can be used to ensures syntactic interoperability for serialization. An API is simply a piece of code that governs and administers the access to a server. It also comprises of the rules software developers should employ to interact with a data source, library, database, a programming language, or a software tool (Hewett et al., 2020). A typical application of API for enterprise digitalization is shown in Figure 4.

2.2.Towards Distributed Ledger Technology Interoperability

Distributed Ledger Technology is simply a type of database infrastructure in which databases are linked in a distributed method across a peer-to-peer network standards and mostly managed by a consensus protocol (Carter et al., 2019; Hawig et al., 2019). DLT is based on cryptographic rules and is deployed by two sides (Lima et al., 2021; Szabó et al., 2022). Each member node in the distributed network has a distinctive credential and retains a duplicate copy of the ledger and participates in the collective authentication of digital transactions across different computing devices within the distributed network (Reegu et al., 2021). Each data transaction is validated by the consensus of most of the participants within the network (Kumar, and Chand, 2021). All data is encrypted and digitally signed to ensure accuracy and authenticity (Lima et al., 2021; Lu, 2021). Each packet of data is referred to as a hash. Hashes are validated as accurate through the common consensus protocol employed which varies depending on the type of DLT. When a hash has been validated, it is included to the bundle of a fixed size termed as a block. The new block is created based on the previous block and is included to the distributed ledger as seen in blockchain (Carter et al., 2019; Xu et al., 2022). DLT has received much reputation as a promising disruptive technology that provide improved security on data sharing among different stakeholders in a decentralized manner (Belchior et al., 2021). It is seen as the key infrastructure for the next generation of digital ecosystem because the data saved is unalterable and tamper resistant. Moreover, DLTs supports other characteristics, such as transparency, trustful transactions, anonymity, decentralization, etc. by eliminating intermediaries (Firdaus and Rhee, 2020; Lipton and Hardjono, 2021).

Despite DLTs having several potentials, the deployment of DLTs within enterprise process comprises of the 51% security attack. This is possibly the most persistent issue faced by DLT as the distributed ledger is spread out over many nodes (Malik et al., 2023). However, the fundamental problem that lies in DLT is the fact that a single user can manages amass majority of the distributed network's capacity. Moreover, within the distributed nodes there is need to validate the transactions to manage the upkeep of DLT network based on transaction costs of miners as an incentive (Alshehri, 2023). Also, the costs of transaction within the network usually gets higher based on the large number of nodes involved in managing both non-incentivized and incentivized traffic. This results to reduced transaction and data storage speed across the distributed networks. Due to the rather low speeds and high transaction costs, it is mostly difficult to scale up this technology in digitalizing enterprise operations (Anthony Jnr, 2023a). Additionally, the landscape of DLTs is still fragmented, as existing DLT platforms are operating in silos. They are deployed as stand-alone, isolated without connecting and sharing data with other legacy platforms (Hardjon et al., 2020; Srivastava et al., 2021). Hence, interoperability has become an important functionality that can enable broad DLT adoption facilitating cross-DLT interaction (Firdaus and Rhee, 2020). Interoperability of DLT also aims to enable communication among DLTs platforms without restrictions (Firdaus and Rhee, 2020).

Research related to DLT interoperability was first carried out by in 2014 in the study "pegged sidechain by Blockstream" (Back et al., 2014), where the author aimed to support cryptocurrency transactions between ledge platforms and Bitcoin (Zheng and Lu, 2021). Thus, there is need for achieving interoperability of DLT, which can occur in the following as shown in Figure 2.

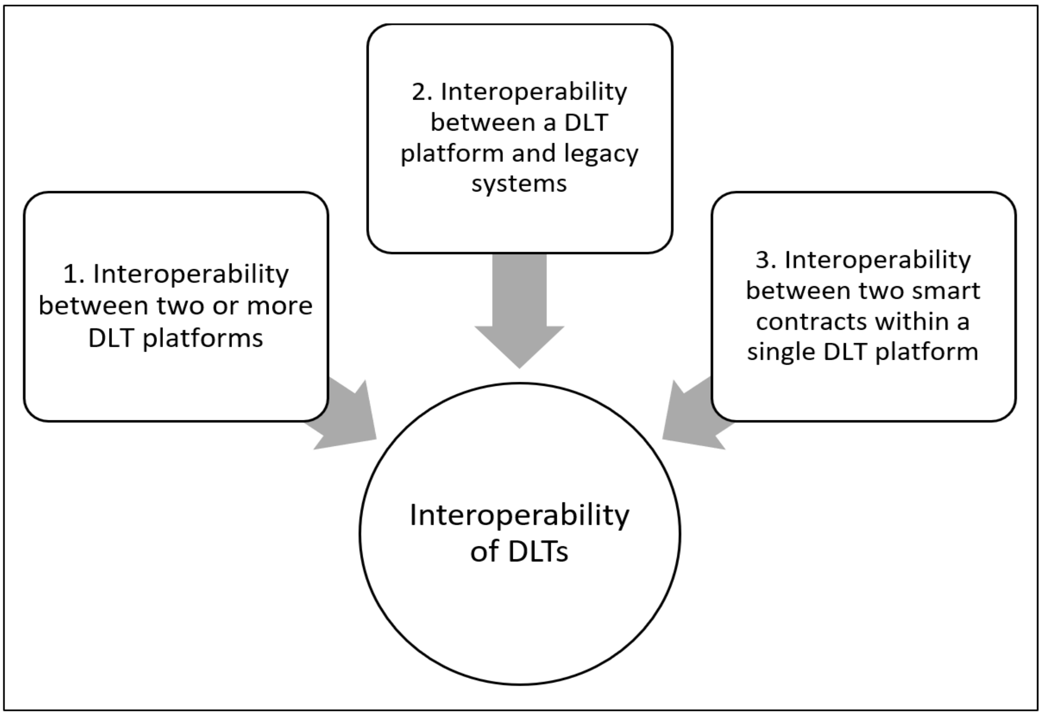

Figure 2. Interoperability of distributed ledger technology

Figure 2 depicts the interoperability of distributed ledger technology which comprises of interoperability between different DLT platforms. The first interoperability cluster is DLT to DLT interoperability which involve exchange of digital asset and exchange of arbitrary data. Most enterprise that adopts DLTs may require arbitrary data exchange. The interoperability of these DLTs involves more than standardizing data format across different platforms but may require employing protocols that supports one DLT such as blockchain to access data from another DLT platform (Hardjono et al., 2019), as seen in Figure 3.

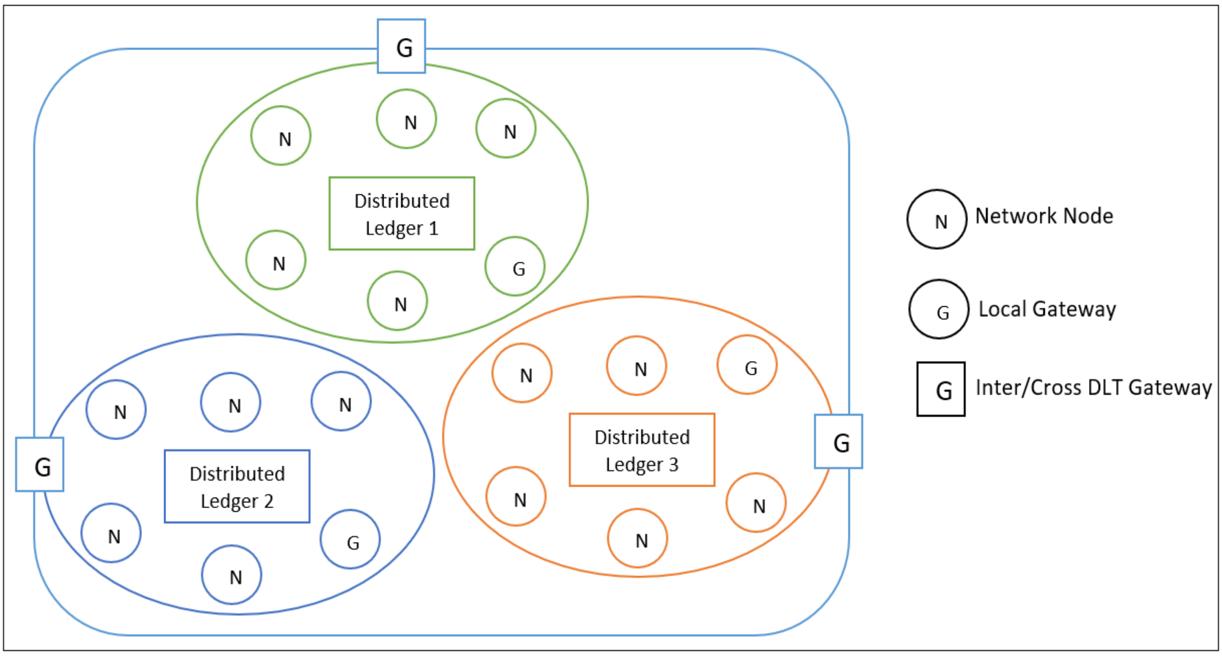

Figure 3. Interoperability between two or more DLT platforms

Figure 3 depicts an example the concept regarding how interoperability between three DLT platforms can be achieved (Hardjono et al., 2019). As seen in Figure 3 the network nodes "N" which are the partners or stakeholders involved in each DLT within the enterprise. Within the intradomain the "G" is designated as local gateway ideally responsible for maintaining of the distributed ledger. The intradomain aid node users to maintain distributed ledger data and validating transactions within a single business domain. Examples comprises of nodes that contribute to orchestrate consensus computations and mining of nodes (Hardjono et al., 2019). Lastly, the bigger "G" denotes the inter or cross domain gateway which enables administrative capabilities such as software update, hardware maintenance, and trusted computing base. This allows different stakeholders groups of nodes to act mutually in the governance of DLT system. The inter domain nodes helps to address inter-domain transactions involving different DLTs that interoperate (Hardjono et al., 2019).

Practically, DLT to DLT interoperability can be achieved using simple programming capabilities, on each DLT platform by employing visibly verifiable signatures for actions that requires transfers or atomic swaps that complete only if partners in each DLT initiatives the transaction. For instance, using bitcoin spendable in decentralized applications such as Ethereum (dApps) (Hardjono et al., 2019; Hewett et al., 2020). For instance, DLT to DLT interoperability entails integration between DogeCoin and Bitcoin, which are two permissionless ledgers or Ethereum and Corda which involves a permissionless and permissioned ledger (Koens and Poll, 2019). Another example of interoperable DLT to DLT include Cosmo network and Interledger which aims at connecting blockchains. Interledger aims on connecting different payment networks and Cosmo network aim on supporting low-level data exchanges across different platforms (Dinh et al., 2019).

Interoperability of DLT to DLT involves reading, monitoring, and making decisions based on events and state data (Koens and Poll, 2019). The state data comprises of the series of transactions carried out at a specified point in time, whereas the event data is typically a transaction. New event is proposed when there is a new state data in the ledger. For example, suppose user A wants to exchange ownership of his/her bitcoins for user B's ether, a token saved on the Ethereum ledger. A token signifies a digital asset of some value. A potential solution is to deploy a centralized exchange, which manages the token exchange between user A and B. However, this mainly goes against the rules of decentralization of DLTs (Koens and Poll, 2019). The second cluster entails interoperability between a DLT platform and legacy systems deployed within the enterprise.

For example, blockchain and a conventional banking payment application. Figure 4 shows interoperability between a DLT platform and legacy systems. It illustrates a typical application of API for enterprise digitalization. As most DLTs such as blockchains have passive infrastructure which makes them to be unable to generate a verifiable-by-others signature, data exchange is the more challenging type of interoperability to attain (Hewett et al., 2020).

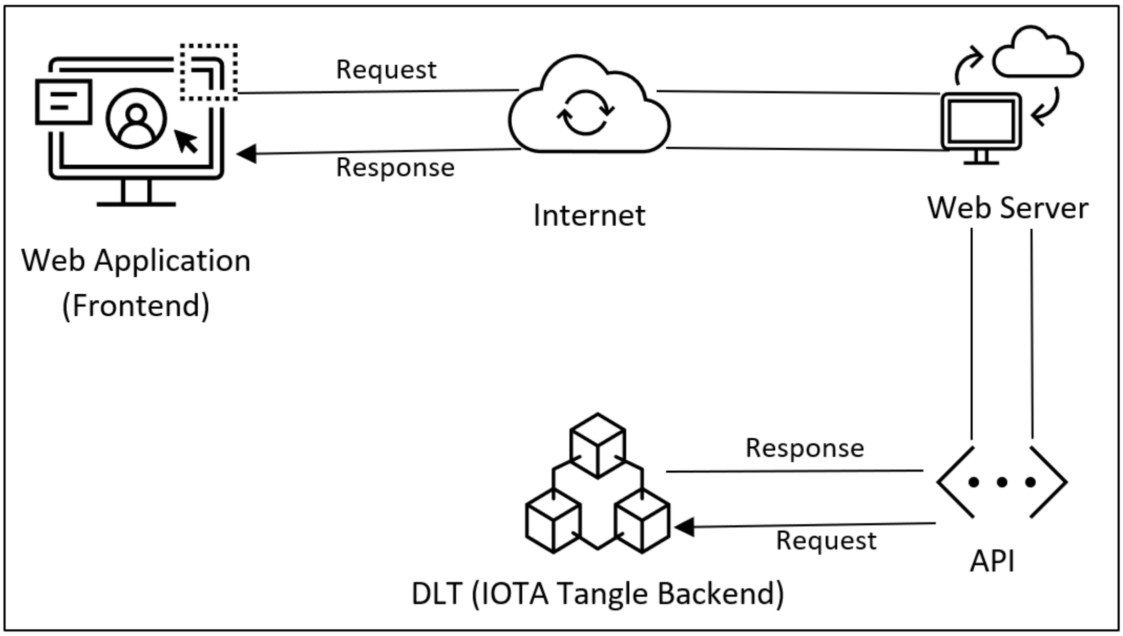

Figure 4. Typical deployment of API to achieve structural interoperability in enterprise

As shown in Figure 4 API is deployed for structural interoperability for exchange of data by enabling IOTA Tangle to be interoperable with another digital platform. This capability permits the use of data on IOTA Tangle to affect the state changes on other digital systems deployed within the same eco-system (Anthony Jnr et al., 2020). The third category comprises of interoperability between two smart contracts within a single DLT as recommended by Koens and Poll (2019). An example of this type of DLT interoperability involves integration between Corda apps which entails smart contracts deployed on a single Corda ledger. This article is more focuses on the interoperability across DLTs platforms and legacy systems as seen in Figure 4 to allow data transactions to occur seamlessly across multiple enterprise systems.

2.3. Interoperable Governance of DLTs

Research related to interoperability and governance of DLT has received little attention from the academic community. But the interoperability and governance of DLT is important as in the future DLTs may evolve to an interconnected eco-system of independent and autonomous digital platforms with different central protocols, stakeholders, and systems (Hardjono et al., 2019). Most DLTs are based on consensus mechanisms/algorithms/protocol which ensure platform integration to achieve a single, immutable adaptation of the distributed ledger (Zuo, 2021). These consensus mechanisms aid actors within the distributed network to agree on data or transactions recorded on the ledger. There are several consensus algorithms adopted today in DLTs and they include Proof of Stake (PoS), Proof of Work (PoW), Practical Byzantine Fault Tolerance (PBFT), etc. (Hewett et al., 2020; Anthony Jnr, 2022b). These consensus mechanisms are based on the types of the DLT (for instance, private, public, and permissioned).

Public DLT permits a participant to be freely involved in the decision making of ledger and it’s grounded on PoW and PoS consensus protocols. In comparison, the private and permissioned DLTs are governed by a set of trustworthy users described to as permissioned nodes based on consensus protocols such as PBFT (Kumar, and Chand, 2021). For example, general-purpose DLTs such as Ethereum, a permissionless or public DLT permits any user to join. Conversely, another DLT named Hyperledger Fabric is a permissioned or DLT which network nodes' identities are visible to all users (Dinh et al., 2019). However, it is expected that in achieving interoperability of DLTs a network of interconnected distributed ledgers platforms with different permissions, incentives mechanisms, consensus protocols, and security protocols and constraints can be integrated to form an internet of DLT. But presently, interoperability is a challenge when permissionless DLTs (which are publicly readable ledgers) interact with permissioned private based DLTs when transactions are executed as confidential data can be revealed which are considered as private (Anthony Jnr, 2022c).

Also, there are issues related to legal ownership of data asset (Hardjono et al., 2019). In achieving interoperability of DLT the concern is how can these consensus protocols be developed to support the digitalization of enterprise operations. Therefore, there is need for considering the governance of DLT as an important feature required in achieving cross-DLT interoperability among different permissioned and public (permissionless) DLT systems, with several platforms communicating with each other to make the actualization of dApps more pervasive and much easier (Lima, 2018). Moreover, the stakeholders of the distributed ledger networks need to specify protocols, define administrative controls over the ledger access for business liabilities and responsibilities according to their organizational needs to avoid ambiguities regarding data ownership (Hardjono et al., 2019). The situation is somewhat more complex in inter/cross DLT systems, which deploy a P2P network of nodes over a geographically dispersed topology where the participation of network nodes are dynamic over time.

Furthermore, adhering to the European Union (EU) General Data Protection Regulation (GDPR) which controls the collection, processing, and storage of personal data within DLT platforms is challenging and this may impact interoperability of DLTs and legacy systems. Issues related to roles and accountability on how to recognize a data controller in a permissionless DLT, anonymization of private data and to what extent can personal data be stored in a distributed ledger (Hawig et al., 2019; Lohachab et al., 2021). Also, GDPR rights conflicts with how to remove or rectify personal data which are saved in a distributed ledger such as IOTA Tangle which is immutable. Lastly, in a DLT which user is responsible for managing and requesting the unambiguous, freely, informed, and specific consent from a data subject, particularly if the data controller is not listed within the distributed network.

2.4.Related Work

A few studies have explored DLT interoperability from different perspectives. Among these studies Domalis et al. (2021) designed a conceptual interoperable and trustable decentralized approach for cross-border eGovernance and citizen-centric for dissemination common public services. The author suggested an artificial intelligence-based solution that facilitates stakeholder to contribute towards a decentralized network for efficient service delivery and big data exchange that promotes an interoperable cost-effective, and secure efficient services. Another study by Lima et al. (2021) implemented a mechanism for validating the immutability and integrity of data using IOTA. IOTA was employed as a supporting tool to guarantee tamper-proof, traceability, data immutability, and characteristics. The authors employed a mechanism to validate the integrity of data via hash functions within IOTA network to enable a reliable ecosystem for digital health records.

Prada-Delgado et al. (2021) developed a blockchain-centric crypto-anchor system for interoperable good authentication. The study presented a platform that offers a generic approach of an object via a blockchain architecture for the system based on Hyperledger Fabric. Additionally, Firdaus and Rhee (2020) carried out a review on blockchain interoperability and possible current solutions. The researchers defined the architecture for blockchain interoperable and provided guide on such implementation. Also, the study investigated several issues related to blockchain interoperability, applicable use cases, and possible research direction. Hardjon et al. (2020) examined the interoperability of distributed systems aimed at bringing to the front the concept of interoperability, manageability, and survivability of blockchain based systems. Findings from the study presented a developed viewpoint for an interoperable blockchain architecture, and further outlined some design standards that promote interoperability. Besides, Hewett et al. (2020) presented a framework to facilitate deployment of blockchain in supply chains. The authors presented different viewpoints on governance of the blockchains which is impacts the interoperability of blockchain. The study designed a blockchain interoperability layers which is important when considering the compatibility requirements between different blockchain platforms.

Dinh et al. (2019) presented a blueprint for interoperable blockchains to support interaction among various blockchains to overcome the data standardization challenges. Using smart contracts running in various blockchain systems the blockchains can communicate. The study also discussed other issues related to cross-chain communication, access control, and general cross-chain transactions. Likewise, Hardjono et al. (2019) researched on interoperability architecture within blockchain based autonomous systems grounded on the design viewpoint of the internet architecture as the basis to ascertain key design standards. The study also highlighted some of the setbacks faced in the development of the internet architecture analogous to the development of an interoperable blockchain architecture. The objective is to design an interoperable blockchain architecture, in which common elements and standardization is employed for the blockchain architecture to decrease development costs, improve reusability, and better interoperability.

Koens and Poll (2019) assessed interoperability options for distributed ledgers. The authors described a set of important properties with which interoperability-based solutions can be assessed. Employing these identified properties, the study systematically evaluated the most common option and recognize several issues. Also, the properties are suggested to be employed in practice to evaluate interoperability solutions to determine which type of solution fits best. Karoudis and Magoulas (2018) presented a user model interoperability that aids sharing of learner data by employing DLT and the experience API. The author employed a peer-to-peer method for retaining and disseminating data with limited trust. The suggested approach is underpinned by the experience API standard excluding the need of a mediating body. Lima (2018) proposed an open and interoperable standard for DLTs and blockchain. The author focused on proving an understanding on how existing open standards can support global blockchain development and implementation in achieving an ecosystem for this technology.

Findings from this section reviews several studies that have investigated DLT interoperability. However, none of these studies investigated the interoperability, standardization, and integration of DLTs. Moreover, none of the presented studies explore how interoperability of DLTs such as IOTA Tangle can be achieved with legacy systems. Also, there are fewer studies that explored the multitude of technicality and complexities, that existed in achieving an interoperable DLTs with legacy systems. Thus, this current study adds to existing body of knowledge by providing theoretical and practical insight on DLT interoperability and further presents an architecture that show how interoperability can be achieved in DLTs and legacy platforms grounded by application programming interface gateway.

3. Methodology

3.1. Theoretical Background (Factors that Influence the interoperability of DLTs)

DLTs provides an immutable and trusted transaction employing a distributed decentralized method, where each user node possesses the same permission with an equal degree of certainty. Some DLTs allows trusted third-party platforms to store data and retrieve them in the database (Kumar, and Chand, 2021). Ideally, the interoperability of DLTs provides the ability to connect and disseminate data across different network ensuring secure and seamless interoperable digital services. Currently, multiple DLTs are being developed (such as Bitcoin, Hyperldeger, Ethereum, CORDA, IOTA Tangle, etc.), each having distinct technological designs and protocols. Most have similar terminology for mining node, transaction process, etc. but there is little or no interoperability among these DLT systems (Hardjono et al., 2019). Hence, several factors are needed to be considered for DLT platforms to be compatible for attaining interoperable communication (Firdaus and Rhee, 2020). These factors are presented in Table 1;

Table 1 Factors that influence the interoperability of DLTs

Interoperability factors	Description
Functionalities provided	This involves what interoperable functional solutions will be offered when two or more DLTs and systems integrate (Firdaus and Rhee, 2020). For example, a data can be sent to and from one distributed ledger to another distributed ledger.
Third party reliance	DLTs aims to be decentralized, implying that there should be no reliance on external party. In some approached employed by DLTs such as notary schemes there is mostly strong dependance on the role of third parties referred to as set of notaries (Firdaus and Rhee, 2020).
Extendibility	This involves the number of DLTs and systems that are to be integrated together for an interoperable enterprise process. This factor also involves the direction in which the distributed ledgers can be operated (one-way interoperability or two-way interoperability). For instance, BTCrelay permits Ethereum ledger to access data from Bitcoin ledger, but Bitcoin ledger lacks the appropriate scripting capability to read data from Ethereum ledger (Firdaus and Rhee, 2020).
Scope	Entails how the state is to be stored once interoperability has been attained. E.g., permissioned based DLT store state based on the limited number of contributors as the state is not stored beyond

	the scope of available ledger contributors. In contrast, to permissionless based DLT where all users can access the state from the distributed ledger as the state is stored as public and available to all participants (Firdaus and Rhee, 2020).
Scalability	Scalability refers to the allowed number of data that can be handled per second. In achieving interoperability, the processing speed may decrease as more digital platform are integrated within the enterprise data eco-system solution or to the ledger connecting to the solution (Jnr et al., 2021).
Existing regulations	Normally, permissioned based DLTs are adopted by corporate organizations and thus are subject to legislation. Hence must conform with stipulated rules and regulation. In comparison, permissionless based DLTs are less bounded to these legislations. These conditions may impact the interoperability of permissioned and permissionless DLTs (Firdaus and Rhee, 2020).
Governance approach	Governance of DLTs refer to the administration of the human-driven guidelines for node participants, the rules of usage that are encoded within the DLT hardware and software and the planned application of the DLT platform programmed as smart contracts (which are stored as procedures programmed on nodes) (Hardjono et al., 2019). Overall, the governance controls data ownership and business models that the enterprise can adopt for management of incentives within the DLT ecosystem (Hewett et al., 2020).
Rate of confirmation	The throughput or speed of DLT system relates to the speed taken for data confirmation and its mainly based on the size of the participating node users (Hardjono et al., 2019).
Robustness of consensus	Another critical element is the size of the node population involved in contributing to the consensus mechanism deployed. As this will impact the interoperability goal across DLTs systems.
State of permissionability	The state of DLT either permissionless or permissioned specifies the degree to which individuals can join the DLT system. The interoperability across permissioned based DLTs poses additional issues regarding how data can be saved on the distributed ledger (Hardjono et al., 2019).
Extend of anonymity	There are two extent of anonymity that is pertinent to DLT platforms. The first relates to the anonymity of participants (i.e., anonymity of users' identity), and the second is the node anonymity of the contributors in managing transactions (e.g., user nodes involved in each consensus request) (Hardjono et al., 2019).
Security of nodes	The robustness of DLT system comprises of a P2P network of user nodes and is prone to security of the distributed network. If nodes are compromised the integrity of the DLT system degrades considerably (Hardjono et al., 2019). Also, the transparency and immutable may influence data privacy regulations (Hawig et al., 2019).
Type of update method	The update method authenticates how the distributed network achieves consensus on the distributed ledger state. This update method is stated as the *consensus mechanism* which refers to Bitcoin's PoW, PoS, BFT, etc. (Koens and Poll, 2019). The update method may influence the interoperability of DLTs.
Cost incurred	Transactions within DLTs may incur certain processing fee and these fees may vary depending on the DLT platform. Also, the disparity in fees may be high that some enterprises may choose not to integrate DLTs due to high fees charged, and this may influence the interoperability across different platforms (Firdaus and Rhee, 2020).
Use of native token	A native token refers to the token that symbolizes some value on a specific ledger and is integral to the distributed ledger, e.g., ether or bitcoin. In comparison, non-native tokens represent any asset that is not essential to the distributed ledger, e.g., a token can be a physical asset, data source, etc. Normally, in permissionless based DLT contributors which proposes new ledger states collect native tokens. Permissioned ledgers normally use a consensus mechanism that does not need a native token. But a permissioned based DLT such as Corda does not include a native token (Firdaus and Rhee, 2020).
Technological development	DLTs are comparative new kind of databases and due to technological advancement, there are newer changes being made to existing DLT platforms. This may impact the interoperability between two or more DLTs, as advancement to one of these DLTs may influence the interoperability. For example, change in the consensus mechanism of a DLT, will considerably impacts the time taken for consensus to be achieved and this will impact the interoperability (Firdaus and Rhee, 2020).

3.2.DLT Interoperability Methods

The types of DLT interoperability are classified based on the technical viewpoint comprises of cross-authentication, oracle, and API gateway (Firdaus and Rhee, 2020), as seen in Figure 5.

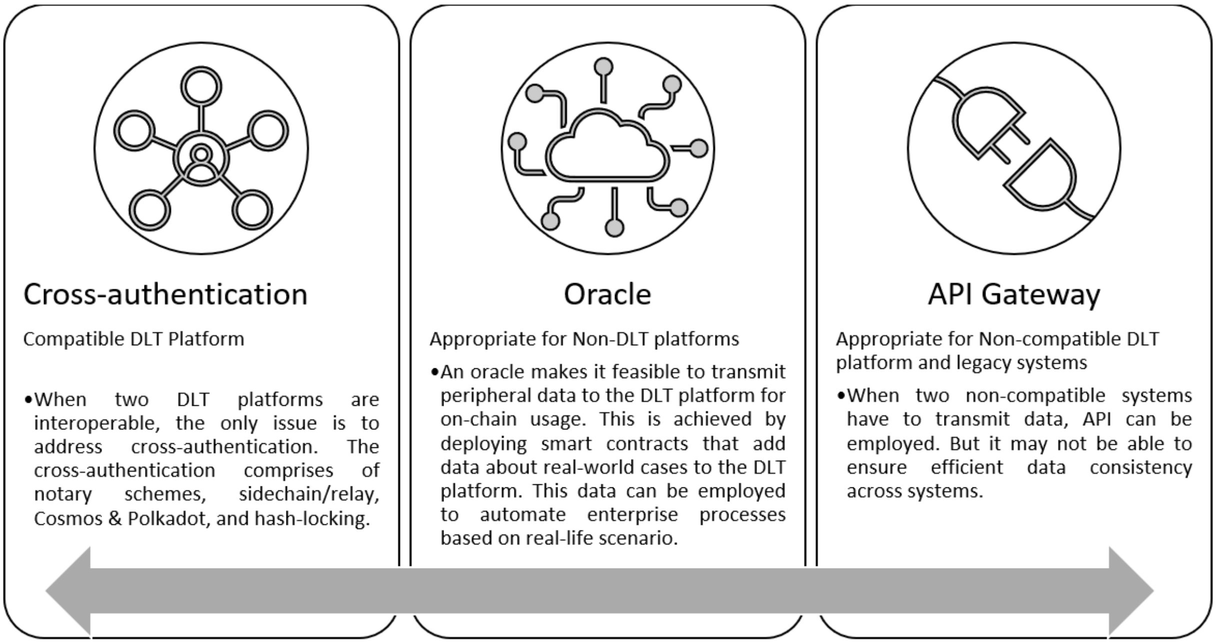

Figure 5. DLT interoperability methods

Each of the classification of DLT interoperability illustrated in Figure 5 are described below;

3.2.1. Cross-authentication

This classification employs different techniques (notary schemes, sidechain/relay, and hash-locking) to enables DLT interoperability without utilizing a main trusted party except from the notary schemes. However, notary and relays schemes aid arbitrary data exchange usually required for more advanced interoperability of enterprise operations. But the relays technique specifically is yet to deployed to support interoperability in enterprise (Hewett et al., 2020). The cross-authentication techniques which comprises of notary schemes, sidechain/ relay, and hash-locking are described further;

a. Notary Schemes

Notary schemes are method performed by trusted third parties called as notaries that facilitate participants on DLT platforms. The notaries implement agreement via some type of consensus protocol and also issue a digital signature that can be utilized to confirm a transaction within the distributed ledger. The notary schemes are one of the easiest approaches to attain the full suite of cross-DLT interoperability. Nevertheless, they are based on trust granted by a centralize body which goes against the key concept of DLT, namely decentralization. But this approach can be appropriate in situations where a consortium can agree on a central authority to administer the notary scheme (Hewett et al., 2020). Additionally, if the adoption of DLT in the enterprise solely relies on the immutability of distributed ledgers and does not necessitate the replacing of formal trust in a central body with a systemic trust via decentralization, the notary scheme can be employed as a feasible option. Conversely, if multiple enterprises are involved in the adoption of the same DLT such as in on a permissioned based DLT the notary schemes would not be suitable to achieve interoperability.

b. Sidechain/Relay

Sidechain/relay refers to the secondary DLT that runs alongside the main distributed ledger deployed to read and validate the state or events on another DLT platform without the need for a trusted third party. More precisely, a relay is an agreement on the DLT platform that works as a light client of DLT platform standard for evoking verification procedure to validate data headers added into the smart contract. This supports "DLT platform 1" ability to identify event changes on "DLT platform 2", without utilizing a trusted party. The relay uses secure message to transmit across two DLT platforms permitting each DLT platform to perform data transactions on its own state device using the latest versions of data from the other DLT platform. The drawback from this approach is that it is quite difficult to connect DLT platforms that do not have similar or desired characteristics. For relays to work optimally the DLT platforms should share certain attributes, comprising of quick consensus and finality flexible multi-signature capability (Hewett et al., 2020).

c. Cosmos and Polkadot

To facilitate interoperability between different DLTs such as blockchain platforms. Relays are usually employed on smart contracts running on a target DLT (Belchior et al., 2021). For example, Cactus implements multiple trusted third party to issue data transactions in several DLTs (Alkadi et al., 2021). Subsequently, different DLT systems including Cosmos and Polkadot suggests the notion of cross-chain data exchange across a single relay chain and several similar chains grounded on decoherence and transaction latency to manage data transactions of multiple components of the system. Cosmos and Polkadot have been improved on this basis, improving the original DLT architecture, facilitating DLTs to exchange assets and data within a variety of heterogeneous DLTs (Lan et al., 2021). Polkadot employs a method for communicating and connecting between similar blockchains on its network, termed as Parachains. Using parachains, Polkadot addresses both the issue of scalability and interoperability.

Furthermore, this aids to attain optimal interoperability amongst chains, create independent and parallel state transitions, and provide shared security across connected chains without affecting decentralization (Koens and Poll, 2019). The Polkadot protocol employs two consensus well known algorithms (Proof-of-Stake (PoS) and Proof-of-Authority (PoA)). Likewise, Cosmos comprises of a network of internet of independent blockchains. It can be seen as a scalable blockchain ecosystem where blockchains can communicate with one other to help improve transaction capacity and the user base (Siriweera and Naruse, 2021). The Cosmos platform enable enterprise to build and connect new blockchain within the Cosmos Hub while establishing a network of interoperability. Cosmos aspires to achieve an interoperable hub where data and transactions can be easily interchanged using a bridge-hub approach to connect the tendermint chains. In comparison of Polkadot, in Cosmos the zones manage the consensus mechanism via decentralized validators.

d. Hash-locking

Hash-locking involves setting up controls on DLT platforms that deploys similar triggers and protocols grounded on the use of the existing hash image. This technique is the mainly employed to achieve DLT interoperability via cross-authentication. But hash-locking is mostly limited in terms of functionality as it supports only exchange of digital asset. Presently, there are two typical types of hash-locking which includes the HTLA mainly for off-chain and on-chain hashed time-lock contracts (HTLC) (Hewett et al., 2020). The HTLA is deployed as a P2P approach that is utilized for financing for several DLT platforms. The HTLC is another solution based on-chain class of DLT-based financing which utilize time locks/hash locks to execute payment to based on a specific time limit which can also forgo the capability to receive the payment, reverting to the sender. This approach aids fully supported bidirectional payment channels and cross-chain atomic swaps among assets on certain types of DLT platforms.

HTLA is a non-smart contract based DLT systems based mostly on off-chain applications. Thus, offer the different integral distributed feature similar to HTLC. Findings from the literature (Hewett et al., 2020), as related to cross-authentication stated that several enterprises have developed alignment approaches that are at different stages of development. These are represented based on the specialized procedures described in Figure 5. Some DLT interoperability methods lay more emphasis on data transfer and therefore provide inadequate support mainly for subjective data transfer. Overall, the relay technique is well employed amongst new enterprise, whereas most DLT interoperability approaches deployed by businesses are more focused on hash-locking technique.

3.2.2. Oracles

Oracle refers to agent or middleman that supports the dissemination of data to the DLT platform towards on-chain adoption. They achieve this by deploying smart contracts which provides data about real-life scenario to DLT systems. These instances of data can be linked to weather, energy rates or status of flights. Data registered within the DLT platform can be utilized to forecast and predict activities. Practically, oracles are no different from other digital platforms such as smart contracts. Nevertheless, to be beneficial oracles are trustworthy since their management is orchestrated by a reliable partner or since they employ cryptanalytic verifications. Oracles deliver a data feed to external events. As such they are established as easy to implement systems. However, oracle do not create definite DLT to DLT interoperability as they are more aligned to supporting DLT interoperable with non DLT based systems. Digital platforms are only as trusted and reliable as the oracles deployed by these systems (Hewett et al., 2020).

3.2.3. API Gateway

API refers to a program that regulates the gateway/right to use a remote gateway and the policies users should adhere to in accessing a library, dataset, programming language or platform. API can be seen as a tried and tested technology and it's easy to implement to support interoperability of DLTs with legacy systems as seen in Figure 4 and 6. API gateway provides access point are managed by several APIs that categorizes the calls being handled by the core design to make simpler the knowledge for the users or the data retrieval procedure form a user (Anthony Jnr et al., 2020; Hewett et al., 2020).

APIs receives many requests from clients and turns them into a single request to decrease requests from the client to the application. Therefore, enterprises may choose to deploy API to be used as an extra external layer linked to the DLT platform. Although, findings from the literature suggest that deployment of APIs may not eventually guarantee data consistency across two or more DLT platforms. Overall, this study will employ this approach to achieve interoperability in DLTs and legacy systems.

3.3.Chosen Method

DLT is an emerging infrastructure and there is little information available that classifies, defines, and define frameworks/architecture that support DLT interoperability. Therefore, the enterprise architecture is employed in this research as a reference model to plan the key concerns, stakeholders, viewpoints, and description into an organized solution. This study employs an enterprise architecture developed in prior studies (Jnr et al., 2020; Jnr et al., 2021), to help provide a framework to define the stakeholders, enterprises, systems, data, and technological components required to achieve DLT interoperability for sustainable enterprise digitalization. The enterprise architecture modelling based on a top-down view approach is employed to develop the architecture for DLT interoperability. ArchiMate is then employed for modelling of the DLT interoperability. Based on the enterprise architecture framework this study illustrates how IOTA Tangle DLT and APIs are employed to achieve an interoperable data sharing to aid digitalization of enterprise process. IOTA was chosen for the ability to support transparency, automation, cost effectiveness, and maturity. IOTA's offers zero transaction fees and manages large transaction throughputs effectively.

Based on the reviewed DLT interoperability methods. Several approaches can be employed to support DLT interoperability as discussed (see section 3.1). With relays, the state of one DLT is replicated within another DLT, which facilitates callers of the relay contract to validate the presence of a data transaction on the source DLT (Sober et al., 2021). However, relays have associated costs incurred since on-chain authentication is quite expensive, and ledgers (blocks) must be continuously relayed. All the reviewed approaches, except for hash-locking mostly depend on a centralized body for validating the transactions and ensuring assets and data are transferred fairly. Protocols such as the Interledger protocol and the notary scheme requires at least one DLT network which instinctively trusts another entity. Although the reviewed approaches maintain the integrity of data communicated across DLTs, notary-based approaches including Polkadot and Cosmos utilize complex mechanisms to ensure integrity verification, thus making them inefficient.

Besides, all reviewed categories have limited scalability, except Polkadot and Cosmos which directly confront this limitation with the notion of parallel blockchains. Also, other framework-independent solutions would be able to offer cross-chain communication to support DLTs such as Ethereum with Hyperledger Fabric. In theory, all approaches are independent, except for notary scheme because they depend on a specific ledger (block) header structure (Madine et al., 2021). In this study RESTful APIs are employed to provide data from external systems as they serve as bridges between DLT platforms and external data sources. These APIs can facilitate query of data from external data sources and also re-directs data or asset state to DLT platform or smart contract. Furthermore, to ensure the integrity and authenticity of the data "IOTA Tangle" is employed as discussed in the next section of this paper.

3.3.1. Usefulness of IOTA Tangle

As previously stated, IOTA was adopted in this study similar to prior study Giannaros (2021). IOTA is a public DLT developed in 2015 as a DLT that has no trading fees, mining, or blocks. IOTA is a substitute to conventional blockchain architectures for DLTs that employs Directed Acyclic Graph (DAG) technique. DAG based ledgers can provide many benefits over conventional blockchain, including transaction costs, scalability, and performance. Using the directed acyclic graph structured IOTA exceeded conventional DLTs, in terms of its quantum-resistant characteristics, fee-less, and scalability (Sun et al., 2020). It employs Machine to Machine (M2M) principle and was designed particularly for the Internet of Things (IoT) based industry using an interlinked architecture via a Tangle network. Data flow management in IOTA occurs with the exchange of Masked Authenticated Messages (MAM) protocol which offers an encrypted channel for secure data which guarantees that the receiver of any transaction receives data with integrity over a trusted source.

These properties make IOTA Tangle particularly well-suitable for data exchange across enterprise systems and devices. IOTA transactions are grouped, linked, and stored together in a sequential chain called as Tangle as compared to blocks used by traditional blockchain. The design of Tangle allows for an authentication process that takes form as a web structure described as a directed acyclic graph instead of a connected list as is the method employed in blockchain-based DLTs. Transactions within the Tangle can get published continuously, synchronously, and simultaneously. To execute a transaction within the Tangle, a user must authenticate two other transactions. Hence, the more contributors that utilize the Tangle, the more transactions are authenticated, making it extremely scalable. This validation procedure also precludes the need for financial incentives to reward members (Hawig et al., 2019). As stated by Lima et al. (2021) the IOTA community supports two public distributed networks (the Mainnet and the Devnet), each having its own Tangle to which nodes can conduct transactions. Besides, a private node can be implemented and connected to the distributed network.

4. Results

A case scenario approach is employed as suggested by Yin (2009). Data was collected from partners involved in the +CityxChange project. The data helped to validate the layers as seen in Table 2. The collected data also provided evidence on each of the layers as seen in Figure 6.

Thus, this section depicts the findings from the case scenario based on the applications of IOTA Tangle and API in the architecture for interoperability towards enterprise digitalization.

4.1.Overview of Case Scenario

This case scenario illustrate how interoperability is achieved in DLT and legacy system via deployment of IOTA Tangle and APIs in enabling digital energy trading marketplace. The case scenario also depicts the use of gathered and managed data from various sources energy assets to deploy a digital energy marketplace. The digital energy marketplace is continuously operated based on the IOTA module which focus to facilitate a safe data transfer and zero fee micropayments between integrated and traded applications using machine to machine protocol with IoT devices. The digital energy trade solution employs APIs for settling of trade and using IOTA tokens to support trading between partners. Using enterprise architecture framework that comprises of seven layers, a model is designed to show how interoperability is achieving based on the digital energy marketplace use case as seen in Table 2.

Table 2 Findings from case scenario on applicability of architecture layers

Layer	Description
Context	This layer defines the needs of the enterprise and the indicators required, which may also be the KPIs of the organization such as the adoption of DLTs to enable enterprise digitalization.
Service	This layer entails the services to be provided by enterprises involved with a consortium. The services are mostly digital and are driven by the enterprise's goals and the Key Performance Indicators (KPIs). For example, services that contribute towards attaining one or more KPIs specified by the enterprise e.g., enabling macro payment via IOTA Tangle, supporting digital contract among partners, reducing cost incurred during payment, etc.
Business	This layer describes the various enterprises operations that are involved in providing various services. Here the enterprises would usually be organizations that need to co-operate to provide similar service to a specific clients or customers.
Application and Data Processing	Application and data processing layer describes the different platforms that support various digital services. These platforms may support data analysis and processing needed to provide relevant service towards digitalization of enterprise operations.
Data space	The data space provides an outline of relevant data sources both offline and online that could be utilize by digital platforms within the enterprise to provide digital service to stakeholders. This layer is responsible for leveraging on available data such as real time data, online data, meta-data, opening for big data markets and contracts for data utilization.
Technologies	Technologies layer captures the different technologies that support the data sources and digital platforms deployed within the enterprise. The technologies may include hardware such as servers, energy management systems, and other enabling infrastructure such as the distributed ledger infrastructure for data transactions and integrity.
Physical Infrastructures	Physical infrastructures layer entails the sources that provide real time data from IoT devices, mobile phones gadgets equipment, sensors, metering devices, etc. This layer contributes for maintaining integrity and transparency of data.

4.2.Modelling of Use Case Scenario

ArchiMate is used to describe and model the interoperability mechanisms in a logical way, while designing IT and business components for all stakeholders. The graphical representation provided by ArchiMate also help to depict the application of enterprise architecture for sustainable digital transformation. Also, the elements and relationships utilized by ArchiMate is tailored to set modelling concepts which is application for denoting enterprise transformation. Hence, in this research ArchiMate is used as the language to model the findings from the case on energy marketplace. The use case for the digital energy marketplace is shown in Figure 6 modelled in the enterprise architecture to achieve interoperable between DLTs and legacy systems.

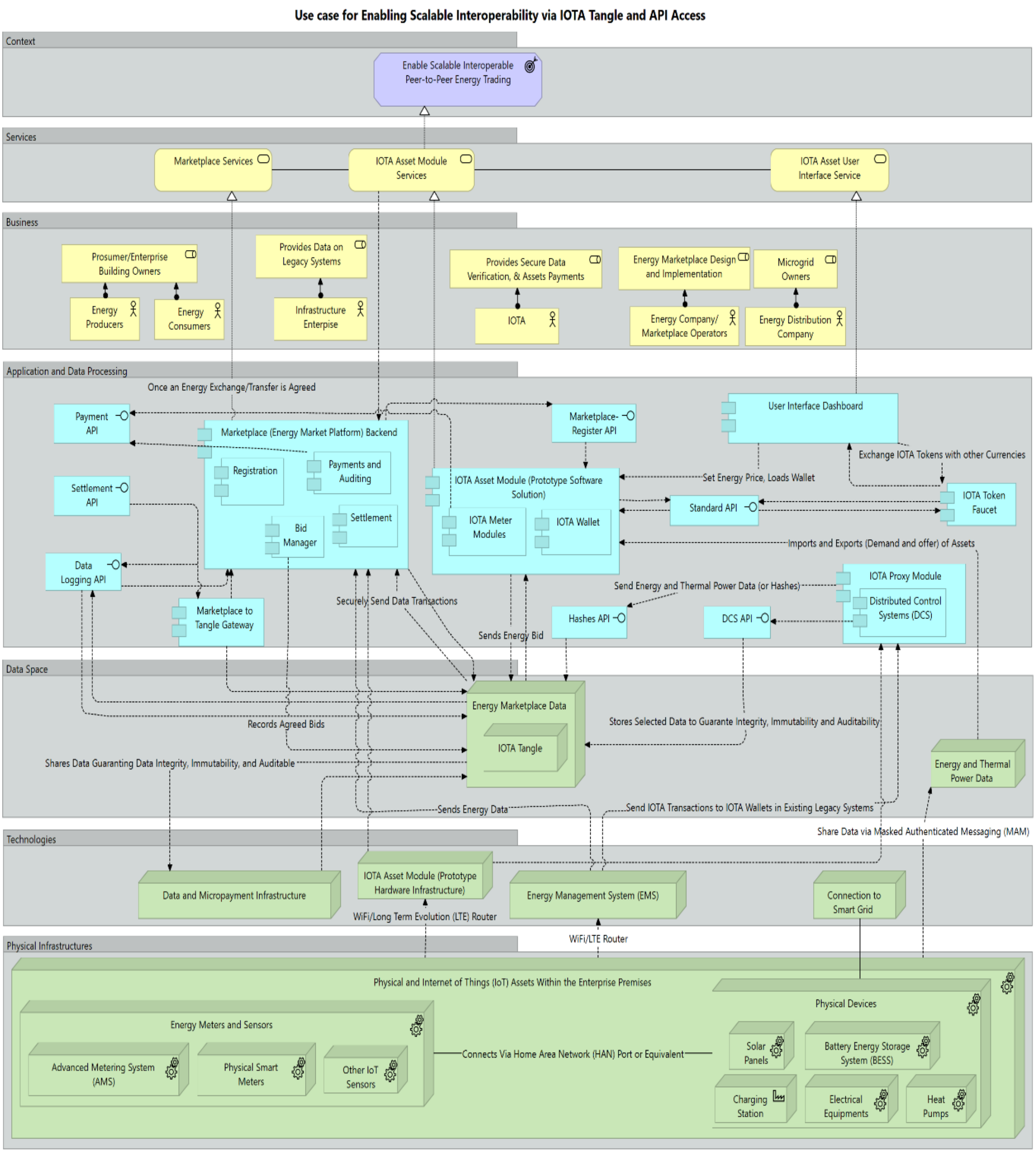

Figure 6. Modelling of DLT interoperability for sustainable enterprise digitalization

Figure 6 depicts the deployment of IOTA Tangle and different APIs to show the application of DLT interoperability for energy marketplace trading towards enterprise digitalization. Each of the constituents within the layers of the enterprise architecture framework shown in Figure 6 are further discussed in Table 3. The findings are based on a practical trial as part of the +CityxChange project which involves partners from different enterprises (energy company, infrastructure company, DLT company (IOTA), electric vehicle rental enterprise, municipalities, real estate company, urban transport company, etc.). Overall, the partners are practitioners involved in providing digitals services which are captures in the architecture as seen in Figure 6. Also, the approach performs well in terms of interoperability in provide a practical digital energy marketplace deployed in a real-world scenario Trondheim, Norway and Limerick Ireland (https://cityxchange.eu/our-cities/).

Table 3 Findings from case study on digital energy marketplace trading in the architecture

Layer	Interoperability Components	Description
Context	• Enable scalable interoperable peer-to-peer energy trading	This layer captures the main goal of the enterprise which is to enable a digitalized marketplace to support matching of bids in the optimum way and communicates the decision to the involved parties via IOTA Tangle.
Service	• Marketplace services • IOTA asset module services • IOTA asset user interface	• The services that support the marketplace comprises of; ▪ Supporting secure data authentication and integrity. ▪ Accepting demand and offers bids. ▪ Facilitating a direct payment among the consumer and producer. ▪ Accepting payments in IOTA tokens. • The IOTA asset module services involve: ▪ Establishing the incorporation of producers and consumers) ▪ Supporting IOTA transactions by setting up buying and selling prices. ▪ Supporting holding and transfer of IOTA tokens in wallet. • IOTA asset user interface comprise of ; ▪ Exchange of IOTA tokens to other currencies such as Norwegian Kroner (NOK) from the wallet to a linked user account. ▪ Setting up of commodity price in IOTA tokens or other currencies
Business	• Energy producers • Energy consumers • Infrastructure enterpise • IOTA • Energy company/marketplace operators • Energy distribution company	• The energy producers and energy consumers are the main actors in the energy marketplace. • Infrastructure enterprise provides data on legacy systems. • IOTA provides secure information on validation and payments processing. • Energy company/marketplace operators aids energy marketplace design and implementation. • Energy distribution company is responsible for the management of microgrid.
Application and Data Processing	• Marketplace (energy market platform) backend	• The marketplace application facilitates a direct payment between partners. It aids direct peer-to-peer payments via IOTA digital currency.

	● IOTA asset module (prototype software solution) ● Marketplace to IOTA Tangle gateway ● User interface dashboard ● IOTA token faucet ● IOTA proxy module	The marketplace further request payments in IOTA tokens buyers and sellers. Overall, the marketplace supports registration, bid manager, settlement, and payments and auditing. ● The IOTA asset integrates the IOTA wallet that process micro payments in IOTA tokens or other currencies. ● Marketplace to IOTA Tangle gateway integrates to the marketplace backend IOTA tangle data ● The user interface dashboard connects to the IOTA token faucet which is responsible for sending payment update to the digital wallet. ● IOTA proxy module receives and sends data to the marketplace database. ● Lastly, the distributed control systems send and retains data to guarantee auditability integrity, and immutability of marketplace data.
Data space	● Energy marketplace data	● The energy marketplace data comprises of all data related to the enterprise stored in IOTA tangle. IOTA Tangle also get data from legacy system via APIs as seen in Figure 6. The energy marketplace data also stores approved bids data to the bid manager. Moreover, other demand and offer of data received from IOTA asset module are stored in the energy marketplace data.
Technologies	● Data and micropayment infrastructure ● IOTA asset module (prototype hardware infrastructure) ● Energy management system ● Connection to smart grid	● All data related to micropayment are received and sent to the marketplace database to guarantee data immutability integrity, and auditable ● IOTA asset module is deployed in this layer as a prototype hardware solution which integrates to the marketplace infrastructure via WiFi or Long Term Evolution (LTE) connection. ● The energy management system sends IOTA transactions on existing legacy systems to the IOTA proxy module. ● Then the smart grid connects to the physical devices, IoT devices, etc. in the enterprise.
Physical Infrastructures	● Energy meters and sensors ● Physical devices	● These are the physical infrastructures deployed within the enterprise to facilitate the energy marketplace for sustainable energy production and consumption. In addition, all physical and Internet of Things (IoT) assets within the enterprise premises are captured as seen in Figure 6. These devices communicate using protocols such as home area network (HAN) port or equivalent.

IOTA Tangle deployed with API ensures data security, authenticity, and easily accessible and immutable to data, adequate for deploying applications with transparency, accountability, and trust within several enterprises that come together to trade renewable energy within the consortium. Furthermore, regarding interoperability of DLTs and legacy systems the integration of IOTA Tangle constitutes the backbone of the energy marketplace solution, which is capable of effectively address the complexity of the energy trading processes, ensuring security, auditability, immutability, and trustworthiness, required in enterprise operation. By combining functionalities enabled by IOTA Tangle and API, the integrated infrastructure allows all stakeholders to control their data without compromising security while achieving interoperability.

Findings from Figure 6 and Table 3 depicts that deployment of API helps to achieve a transparent digital by default, and interoperable by design ecosystem of enterprise digitalization. The findings highlight the different technologies and data sources are deployed to be integrated on top of the API implemented with IOTA Tangle similar to prior study (Karoudis and Magoulas, 2018; Hawig et al., 2019; Masuch et al., 2020; Giannaros, 2021; Lima et al., 2021; Prada-Delgado et al., 2020; Domalis et al., 2021), as illustrated in Figure 6. API is responsible for managing multiple services provided by different dApps, such as the Marketplace (energy market platform) backend, IOTA Asset Module, Asset User Interface (UI) Dashboard, etc. IOTA Tangle and API are deployed to deliver an efficient, secure, and reliable data sharing, communication channels and auditing mechanisms for enterprise digitalization. To disseminate, retrieve, and store encrypted enterprise data the Masked Authenticated Messaging (MAM) protocol is employed as it encrypts data (masking), validates source origin (authentication), and makes a constant data stream within the Tangle until the source stops broadcasting data (messaging).

5. Open Challenges and Recommendations

5.1. Open Challenges for DLT Interoperability in Enterprises

In this digital age interoperability is the ability of different digital platforms and applications to interchange and utilize information. It is also the ability to transmit data between two or more digital systems while consistently keeping the uniqueness and state of the data. Ideally, DLT interoperability within enterprise should aid knowledge transfer and codification, provide fairness of information, accessibility of data and adhering to common data rules (Hewett et al., 2020; Madine et al., 2021). An architecture that supports DLT interoperability composed of different DLT systems, each representing a single distributed data ledger, whereby employing atomic data execution multiple heterogeneous DLT systems can connect. In such systems data recorded in one DLT system should be referenceable, verifiable, and reachable by another DLT system or legacy platform in a semantically compatible approach (Hardjono et al., 2019). But there are several issues that impacts DLTs achieving interoperability with either other DLTs or legacy systems, such as tolerance for diversification, the confirmation of atomicity, security, enhancement of efficiency, and friendliness to software developers (Firdaus and Rhee, 2020).

Other challenges faced by DLT interoperability comprises of how to support reliable access control for smart contracts. While any access policy can possibly be deployed and enforced within a stand-alone smart contract, a good security protocol involves decoupling control policy and enforcement from definite data access (Tenorio-Fornes et al., 2021). Another issue relates to how to support common cross-DLT transactions, for example in blockchains where they are different to cross chain deals and atomic swaps. A well-known challenge is how to facilitate communication among smart contracts, which is presently not feasible for contracts in different DLTs (Dinh et al., 2019). Data standardization is another challenge faced in achieving DLT interoperability. For collaborators to share information within or across different DLT platforms, all data must adhere to a similar data format to ensure standardization as this help all stakeholders to understand the information presented. But most DLTs employ different standardized data representation which makes DLT platforms interoperability difficult resulting to different standards with diverse data attributes (Hewett et al., 2020).

Moreover, there are different legal framework employ by DLTs across the world. Hence it can be challenging to determine data owner across the distributed ledger network because of the decentralized characteristics of DLT platforms, which makes it difficult to specify who is legally in charge of interoperable DLTs (Wang, 2021). Also, in a decentralized setting, it may be difficult to determine which stakeholder has handled what data, when and where, and consequently to determine who is "accountable" for it, or who administers the information or what jurisdiction pertains in disagreements and who is responsible for data integrity. Since some DLTs employed inherently different consensus mechanisms (e.g., PoW, PoS, Raft protocol, etc.) interoperability is not support by default. But DLT platforms that employ same consensus mechanism may be interoperable. However, findings from the literature (Hewett et al., 2020), argued that even if two DLT platforms utilize same consensus protocol, it can be complicated to synchronize data across DLT platforms with agreement about the order of the data communications.

For example, Corda and Hyperledger Fabric may both employ Raft protocol as the consensus mechanism, but each of these DLTs employ different standards regarding how data is stored, how data persists, and which stakeholders contributes to the consensus mechanism. Additionally, there are proprietary modules in private based DLTs. This is because private based DLTs are mostly permissioned and varies greatly from public based DLTs particularly in terms of infrastructure constraints which may affect interoperability among DLTs. Although, the private based DLTs do not demand computing power and consumes less electricity. They also can accomplish high performance in data transaction processing (Wang and Nixon, 2021). Accordingly, they can be utilized in enterprise operations such as in data centers or in virtual private clouds (Hewett et al., 2020).

5.2. Recommendation for DLT Interoperability in Enterprises

Over the years there have been considerable advancements to address DLT platforms interoperability challenges. A few approaches have been employed to achieve DLT interoperability and one of such includes the adoption of more effective consensus protocols to improve throughput and latency. This helps for better use of available distributed network resources and enhancing data processing throughput of payment transaction channels to decrease the transactions required to be processed and stored within the distributed ledger while ensuring better performance (Gabizon et al., 2020). Additionally, standards can be employed to support DLT interoperability. Standards helps to create a common language compatible with different software to be designed and developed towards achieving interoperability across several platforms. Presently, there are some standards development initiatives going on globally such as ISO/TC 307 blockchain, W3C, IEEE DLT/blockchain standards, EEA, ITU-T, etc. to help achieve DLT interoperability (Lima, 2018).

These type of standards focuses on enforcing enabling mechanisms and crucial building components of DLT technologies, such as client interfaces, consensus algorithms, data formats, decentralized identity management requirements, etc. These standards are developed by global organizations and industrial associations/alliances with support from the end users and development community on improving interoperability of DLT platform. Hence it is suggested that newer DLT based standards should be developed based on existing guidelines and principles for DLT standardization. Hence using a common standardized data syntax and format that will be understood by almost all DLT based systems are recommended (Hardjono et al., 2019). Another type of data standards includes HL7 FHIR and HL7 version 2 which are developed to support interoperability through uniform data structure. These standards aid digital platforms to manage and move pertinent data more rapidly. FHIR standard is built on RESTful web services and utilizes modular components as resources. FHIR supports JSON and XML data formats which are both widely used as machine readable (Carter et al., 2019).

Furthermore, gateways can be used to facilitate DLT interoperability in enterprises. Also, for DLT interoperability peering agreements can be developed specifically for DLT interoperability and governance. Such peering agreements should incorporate clear identification of different gateways which support peering. The peering contract may include the device certificates, device status attestations, software, and hardware manifest (for instance hash of manifest), root certificates, etc. Besides, minimal trust establishment parameters and mechanisms should be specified. A peering agreement should indicate the establishment protocols and trust negotiation of parameters such as the main management protocols, the size of key parameters, standards compliance required, minimal assurance level required, etc. More importantly, the liabilities and warranties should be specified. These are similar to the DLT peering contracts (Hardjono et al., 2019).

Researchers such as Dinh et al. (2019) mentioned that Cosmos' inter-blockchain communication (IBC) and Interledger Protocol (ILP) are two of the latest alternatives to support DLT such as blockchain interoperability. ILP is mostly specific to cryptocurrencies, and it's developed to optimize the sending of payments from one blockchain to another. It is based mostly on payment channels, and therefore does not generalize to other DLT applications. In comparison IBC is developed as a more generic communication protocol which manages data transfer, authentication, and connection trustworthiness. Presently, IBC is in its early stage of development, and it requires intrusive changes to the DLT stack to be deployed as it needs to be totally integrated with the state-machine element of the DLT node.

6. Discussion and Implication of Study

6.1.Discussion

The rapid adoption of digital platforms such as DLTs has brought an unprecedented impact to enterprise operations. DLTs aids towards the modernization of enterprise services towards the transformation of business process (Giannaros, 2021). The adoption of DLT platforms hold great potential to help improve information exchange towards archiving open and integrated services (Hawig et al., 2019). But are faced with achieving interoperability of DLT platforms and legacy system. Interoperability aids digital systems to exchange and make use of data. It also aids different platforms to collaborate and transfer asset or information between two or more systems while ensuring the consistent state and uniqueness of the entity (Hewett et al., 2020). However, most studies on DLT applications in enterprises have focused on designs and implementation for verifying the integrity and immutability of DLTs such as blockchains. There are fewer studies that have shown the practical use case application of DLTs such as IOTA to support bidding and trading services within enterprise domain.

Therefore, this study aims to promote DLT interoperability towards enterprise digitalization to enable the integration of data generated from different devices and systems deployed to support interoperability among procedures from different stakeholders. Respectively, this study explores DLT interoperability towards enterprise digitalization. Findings from this study shows how interoperability can be achieved among DLT platforms and legacy platforms based on based a case study on the applications of IOTA Tangle in an enterprise architecture for buying and selling of energy showing the potential of DLT for enterprise digitalization. The findings were modelled using ArchiMate to illustrate how interoperability can be achieved in DLTs grounded by application programming interface standardization that enables IOTA Tangle to communicate and share data across the enterprise network.

Findings from the literature reveal that DLT interoperability has emerged as a theme of much debate in industries. As researchers examines if DLTs can speak to each other and will enterprises get to one standard DLT that will rule all other DLTs (Hewett et al., 2020). Interoperability is key to survivability (Hardjono et al., 2019; Hardjon et al., 2020), of the DLT eco-system. Current DLT interoperability solutions emphasis on linking two permissionless distributed ledgers as permissioned based ledgers may not want to expose their state with a permissionless ledger. Also, DLT interoperability aims to achieve integration of both permissionless and permissioned DLT systems without a third party (Hardjono et al., 2019). The findings from this study examines the potential of DLT (IOTA Tangle) for the exchange of data, by designing and developing a proof-of-concept energy marketplace system. IOTA Tangle was employed since it is a free and open-source platform that supports a reliable environment for digitalization of enterprise services.

Besides, IOTA Tangle supports data traceability, immutability, and tamper-proof attributes suitable for digital services provided by enterprises. Furthermore, this study provides an energy marketplace where prosumers can sell energy as a commodity or services supported by IOTA Tangle and API in a standardized and interoperable interaction of different platforms owned by different partners. IOTA Tangle addresses the traditional issues faced in blockchain-based platforms using Directed Acyclic Graph technique and employing MAM protocol to connect industrial equipment and devices. However, IOTA is constantly an evolving technology, it is suitable as it offers better flexibility, cost, efficiency, and scalability in managing data access as compared to blockchain. Findings from this study is supported by prior study (Lima et al., 2021), which suggest that the tamper-proof, traceability, and immutability characteristics decrease the risk of irregular data processing and storage in IOTA.

Furthermore, the interoperability scene for DLT platforms is still not well developed for enterprise use. As such most businesses adopt Ethereum, and Bitcoin as compared to other DLTs for interoperability between Ripple ledgers and the Corda. Findings from the literature (Hewett et al., 2020) suggest that Relays have been utilized only for permissionless DLT platforms but has not been successful in establishing interoperability for DLT platforms other than Ethereum and Bitcoin. Similarly, Hedera Hashgraph lately stated that the Hedera Consensus Service appears to offer promise for DLT-to-DLT interoperability as it offers a cost-effective and fault-tolerant service which can be achieved in any Hyperledger Fabric network developed. This study advocates for API as a technology that is widely employed to achieve DLT interoperability between “legacy applications” and DLT platforms. Hence, API gateway largely have a high degree of reliability and are easy to deploy for DLT interoperability. However, API solutions are in some use cases still not scalable and leads to loss of decentralization (Hewett et al., 2020). But due to the potential of APIs most DLT solutions in the market today have APIs for integration with external applications and many DLT developers are working on solutions that support total interoperability with other DLT platforms. For example, DLTs such as Ethereum, Hyperledger, Corda,Fabric, MultiChain, Quorum etc. deploys APIs (Hewett et al., 2020).

6.2.Research Implications

Digital transformation enabled by deploying DLTs can decrease managerial burdens, improve productivity of businesses, lessening extra cost incurred in traditional operations to increase capacity, and eventually improve the overall service quality (Giannaros, 2021). With industrial adoption of DLTs such as IOTA, enterprises have been able to address recurring issues of establishing incentives and standards to fully enable cross DLT interoperability. Addressing DLT interoperability can support exchange of data exchange, lessen fragmentation, and need of aggregation, affecting partners identity, consent administration, and access supervision across stakeholders (StClair et al., 2020). Interoperability is essential to survivability of digitalization. The deployment of DLT helps to achieve reachability, referencing of transaction data within the distributed ledgers, scalability, and improvement of enterprise performance. Additionally, DLT interoperability offers a medium on how permissionless and permissioned DLT platforms can connect seamlessly without a third-party involvement.

Findings from this study suggest that syntactic interoperability, semantic interoperability, and structural interoperability are important to achieve connectivity of digital platforms at the value level but does not guarantee it. Syntactic, semantic, and structural interoperability plays an important role in providing technological solutions that can help enterprises in enforcing agreements to provide semantically compatible meanings to cryptocurrencies such as coins, tokens employed in DLT system (Hardjon et al., 2020; Anthony Jnr, 2022). The proposed method has interesting research implications by describing an architecture that aims to support interoperable, open, inclusive, efficient DLT and legacy platforms to support data-driven services. The findings offer implications to enterprises that collaborate towards achieving digital energy marketplace that provides a mechanism that enables bidding, selling of renewable energy and preserving trust among private and public entities involved.

In addition, the architecture enables businesses to participate and achieve a cost-effective, secure and cross-platform distributed network for data exchange and energy service delivery. More importantly, this study provides how enterprises can attain meaningful orchestration and integration of systems, applications, and data sources to build on state-of-the-art digital technologies to address DLT interoperability requirements. This study employs enterprise architecture to model DLT interoperability with legacy systems in enterprise environment. More precisely, findings entail the use of disruptive and innovative emerging technologies, like IOTA Tangle, and the API gateway as a means of maintaining data ownership, data access, and data control as seen in Figure 6 to improve the trust and quality of energy data. The deployment of API standard in DLTs have been reported in the literature. However, there are fewer research that has examined the combination of API with IOTA Tangle technology. Therefore, this study address interoperability via IOTA Tangle and API. Theoretically, the advantages of integrating DLTs such as IOTA Tangle combined with the API could offer adaptive data driven technologies for creating better business models in terms of interoperability.

6.3. Practical Implications

In modern business environment where different partners collaborate. There is a need to achieve interoperability among different digital platforms and data sources, enabling the integrated and seamless usage of data streams (Sun et al., 2020). Likewise, a collaborative network of enterprises which uses different digital platforms is useless if data cannot be seamlessly exchanged across businesses, including retailers, manufacturers, wholesalers, and logistics. But the lack of shared meaning and interconnected data sources is a challenge faced for most DLT-based platforms. Most data from equipment, physical devices, sensor, meters, including wearable devices, are characterized by different standards that impact data integration. Resulting to data silos with heterogeneous data with potential to achieve data-driven platforms. Findings from the literature (Sun et al., 2020), pointed out that integrating data from different sources in enterprise is a challenge, which is aggravated by a lack of interoperable standard or formats in representing resources when digital technologies such as DLTs are deployed with other external systems.

However, attempts are still slow-paced to build interoperable approaches to bridge such huge data silos among DLTs and legacy platforms. Accordingly, the interoperability between the DLTs and legacy platforms in different countries is now a top priority in industries and in academia. Considering the above issues, this article introduces an enterprise architecture as a vehicle to model the actualization of DLT interoperability between IOTA Tangle and API gateway to automates the energy marketplace operation to maintains the integrity of interactions among prosumers, enterprises, and regulators. By taking advantage of emerging digital technologies, such as P2P distributed networks. This solution is based on IOTA Tangle and APIs which interconnects with other applications responsible for ID authentication, energy trading, energy data exchange and energy transactions validation, enabling transfer of bidding to producers and consumers and finally micro-payment. The enterprise architecture modelled in ArchiMate as seen in Figure 6 creates an innovative mechanism for data communication, information sharing and retrieval among centralized legacy platforms and decentralized/distributed applications (IOTA Tangle backend).

The enterprise architecture (as seen in Figure 6) creates an ecosystem with common technologies, systems, data sources that enables an interoperable environment. This approach enhances transparency, security of data exchange, and integration of data dissemination in an encrypted medium which is immutable and increase trust in data retrieved by multiple actors. The IOTA Tangle by design exposes and integrates different APIs to enable interoperability with external systems. The use of API allows writing and reading operations from deployed assets, i.e., retrieving and sending data transactions via trusted channels with encrypted data using MAM protocol. APIs help for authenticating of users and in sending/retrieving data transactions to/from the IOTA Tangle to form a bridge to the distributed network. Findings from this study also show how specific authorized systems were able to connect to different API to interact with IOTA Tangle which connect to physical devices using MAM protocol.

7. Conclusion, Limitation, and Future Research Directions

To ensure business continuity and competitive, enterprise need to evolve for greater agility and productivity to meet new demands. One method is the adoption of digital technologies such as DLTs, which are faced with interoperability issues which prevents seamless, end-to-end exchange of data between different digital platforms. Addressing DLT interoperability will aid to address and pave the way for enterprise digitalization and standardization (Hewett et al., 2020). Therefore, this study presents an enterprise architecture and applied it to illustrate how DLT interoperability is attained with legacy system using the public distributed ledger IOTA and APIs. Findings from this study presented a case study of an energy marketplace enabled by the deployment of IOTA Tangle to achieve a mechanism to enable the interoperability of energy related data stored in the IOTA Tangle backend. ArchiMate was employed for modelling DLT interoperability as regards to the application of IOTA Tangle with API to support a digital energy marketplace platform. Using API with IOTA Tangle data integrity and trust are enhanced in a reliable, secured, and controllable manner.

IOTA offers flexibility and performance to support a reliable environment for digital energy bidding. Although findings from this study is aligned to energy marketplace the applicability of the architecture can be employed to other domains such as supply chain use cases, smart cities scenario, etc. The findings provide the possibility of enterprises to achieve DLT interoperability, thereby addressing fragmented DLT systems. Also, findings present prior studies that explored DLT interoperability from the literature to understand the state-of-art, strength, and weakness. The main findings present the main categories of interoperability in enterprise, interoperable governance of DLTs, technical viewpoint of DLT interoperability in enterprise, and factors that influence the interoperability of DLTs. Besides, findings identified several significant issues, some of which are inherent to DLT interoperability, and recommendations. Further improvements may involve the extending the architecture model to consider the latest regulation and guidelines on private data processing, thus extending the architecture alignment with recent GDPR requirements. Also, future work is expected to explore how access control and data governance can be improved during the deployment of IOTA and API technology.

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